Quantum Sensors for Particle Detection

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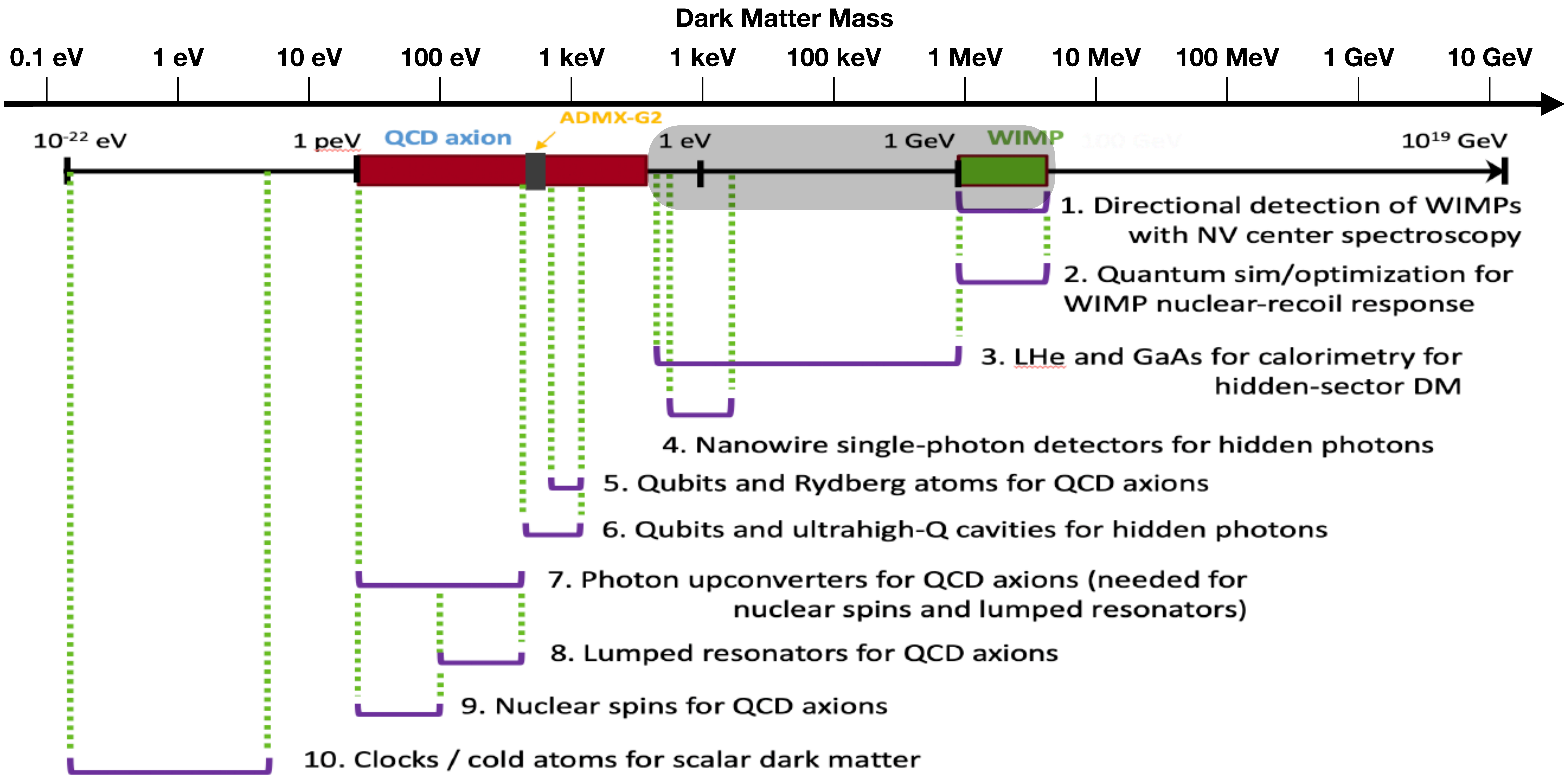
“Quantum” and “Particle” in this talk

- “Quantum” refers to techniques and technologies used in QIS work and being applied to particle detection, but also to techniques measuring single quanta, or signals from single quanta.

- “Particle” refers to localized, particle-like interactions as opposed to coherent mode sensing techniques

Dark Matter and Neutrino Particle Detection



Dark Matter and Neutrino Particle Detection

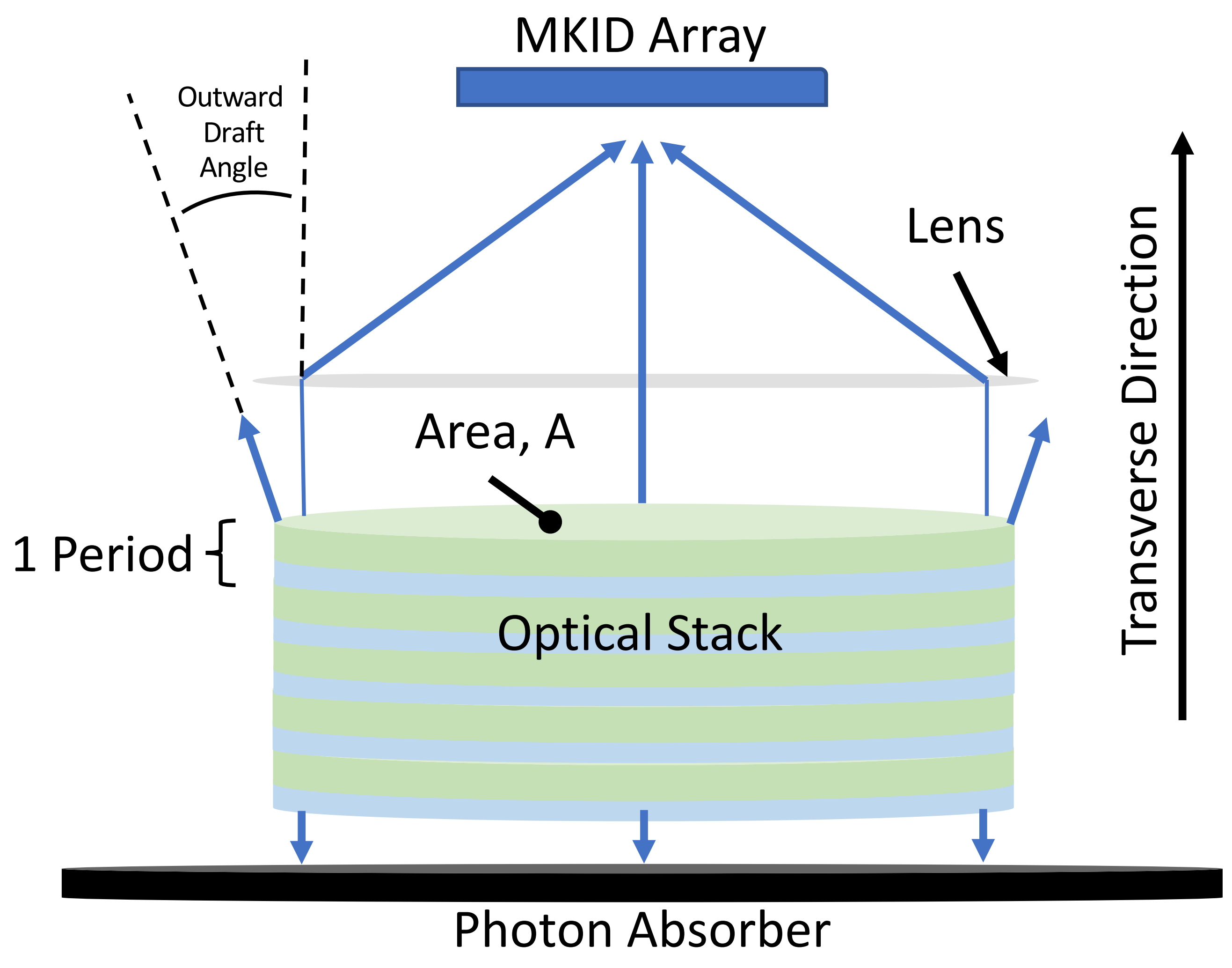
This slide is a work in progress… intended to promote discussion as to how to organize. Please let me know how what I'm missing!

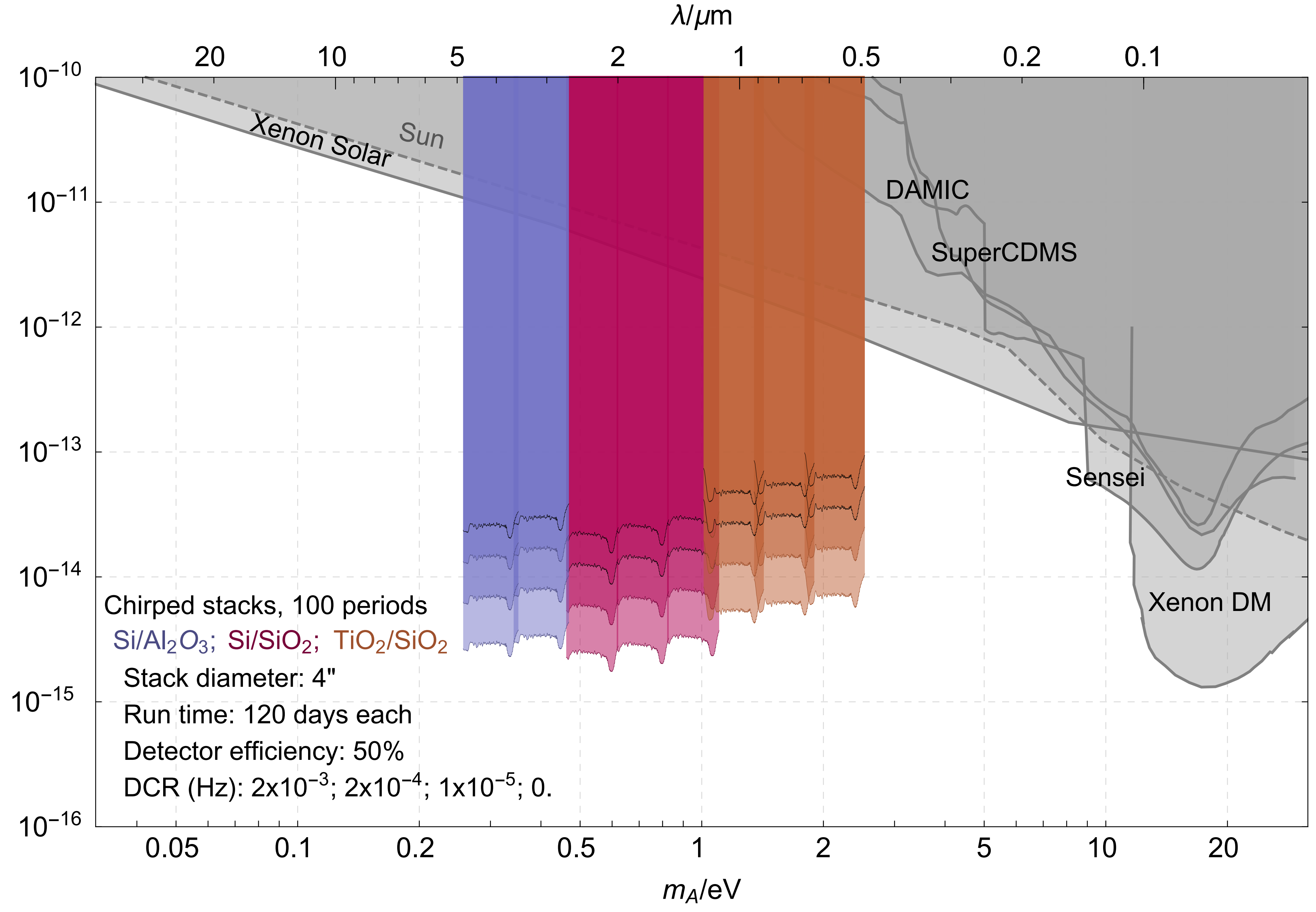
Haloscopes

- Use stacks of different dielectric layers with alternating index of refraction to induce dark photon -> photon conversion

- photons are then focused on to a detector

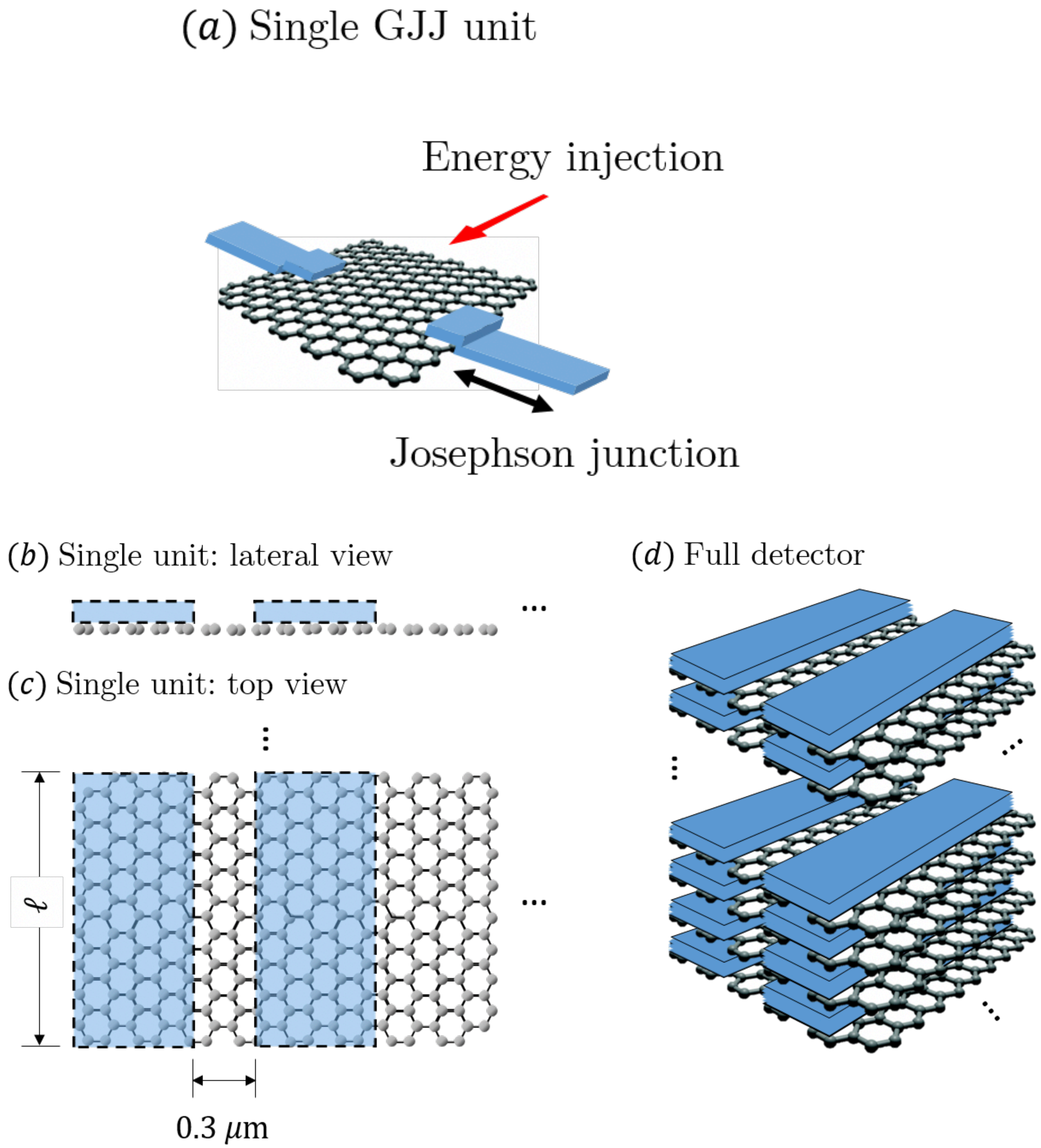
- SNSPD, MKIDs, or other photon detectors could be used





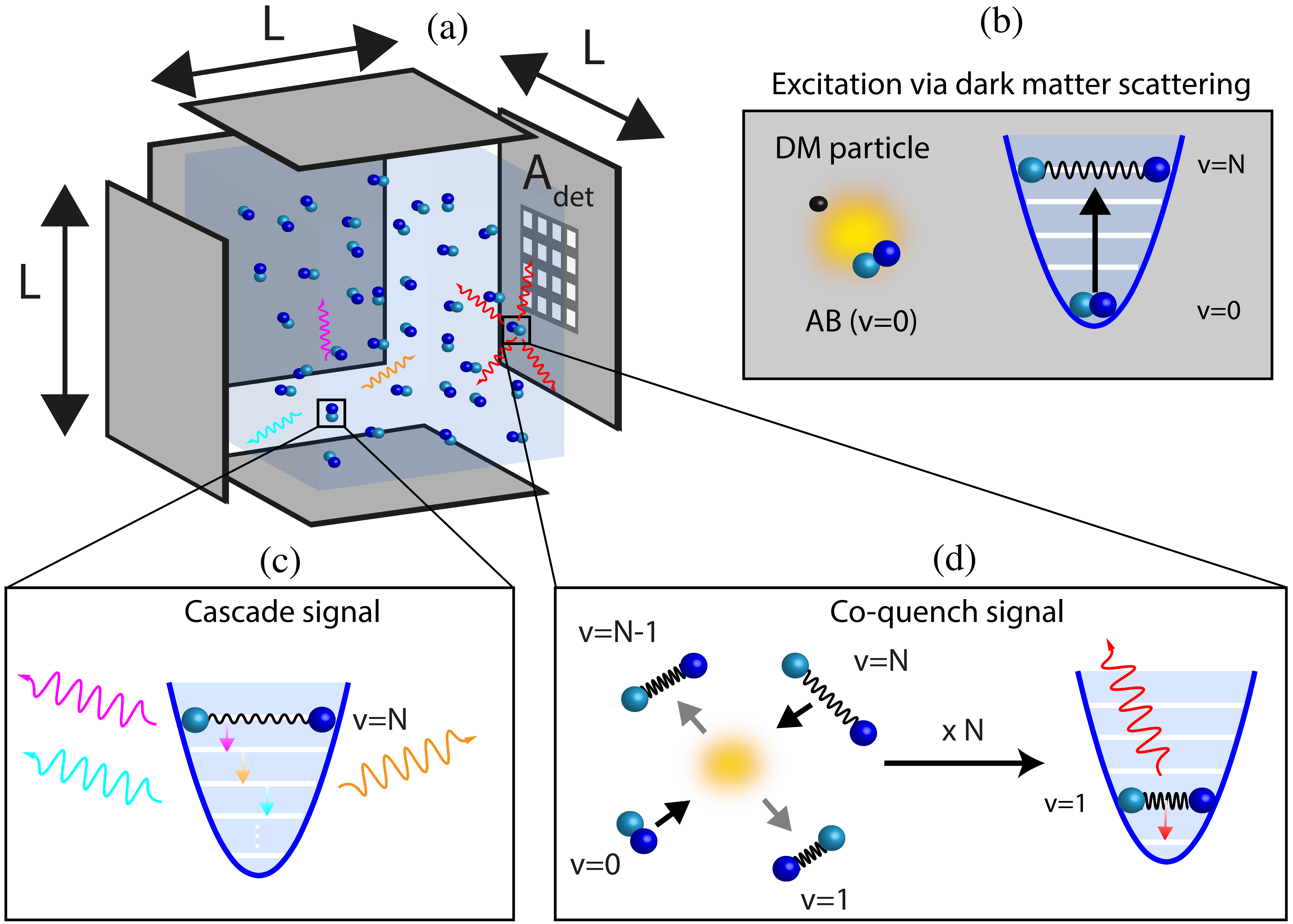
Graphene Josephson Junctions

- Monolayer graphene acts as the normal layer in a SNS Josephson Junction.
- Injected energy is sensed by the change in the JJ from its zero-voltage to resistive state.
- Sensitivities equivalent to 0.13 meV have been demonstrated through NEP bolometric measurements.
- Sensitivity to electron recoils from 0.1 keV dark matter possible



Molecular Excitations and IR photon detection

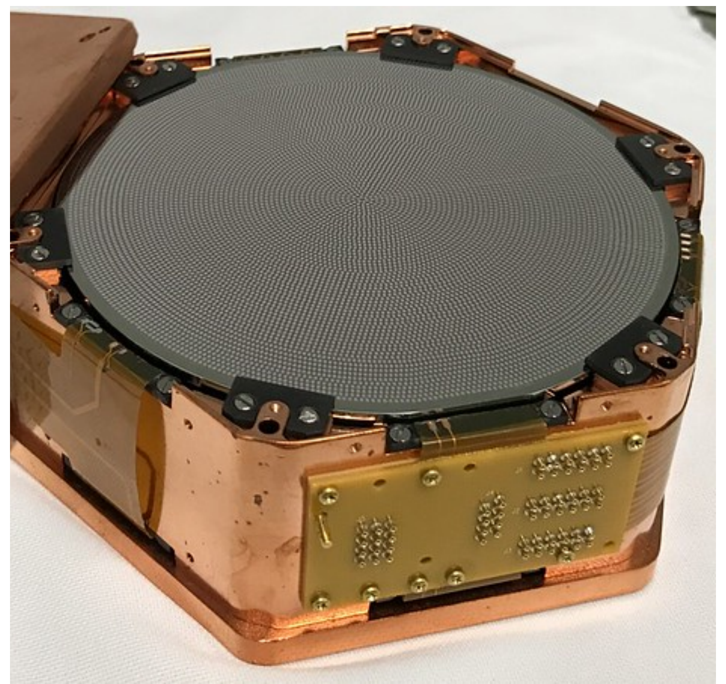
- Dark Matter interacts with low-pressure CO molecular target. Molecule goes to excited state, and relaxed by emitting an IR photon
- IR photon is sensed at surfaces with SNSPDs or other photon sensor.

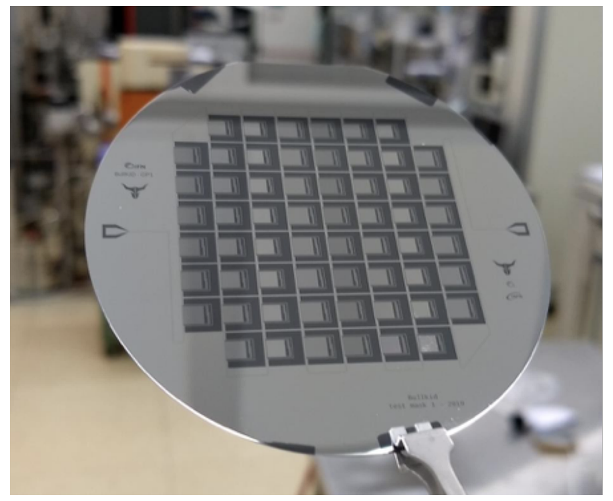


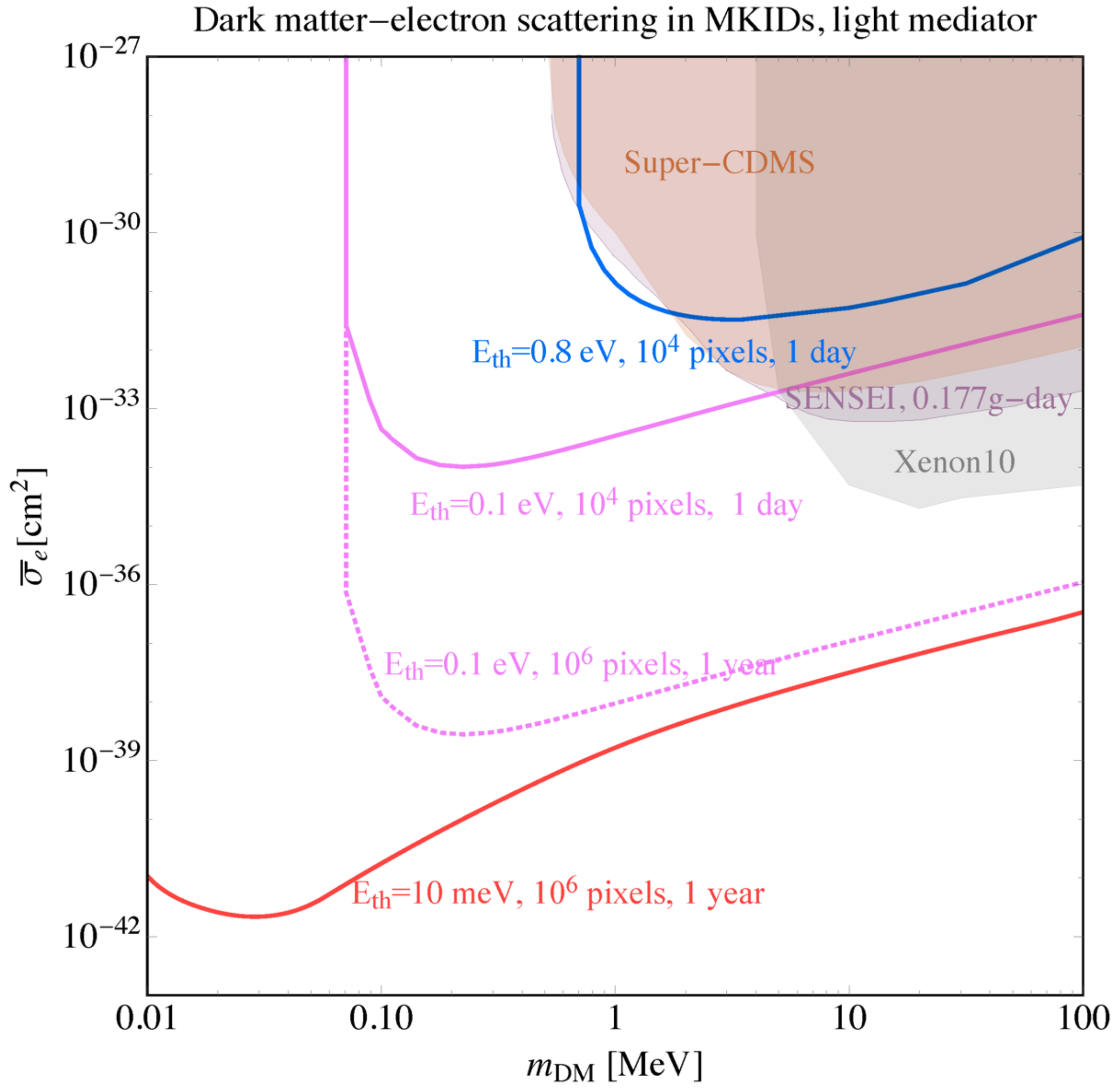
TES / KID / STJ / NTD / MagCals…

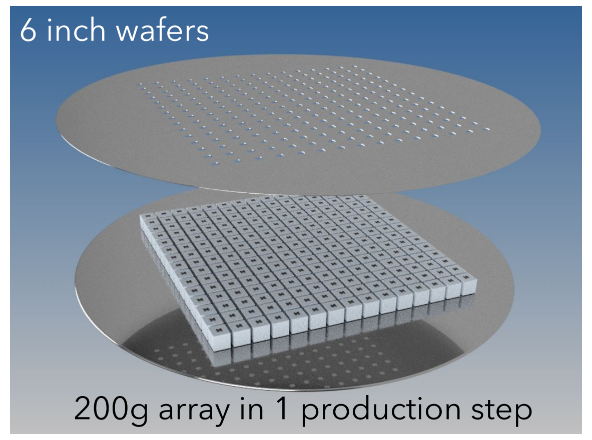
- Low-temperature phonon/quasiparticle detectors are being proposed by a large number of experiments, for dark matter, CMB, 0vBB, CEvNS, Cosmological Surveys, and other applications.

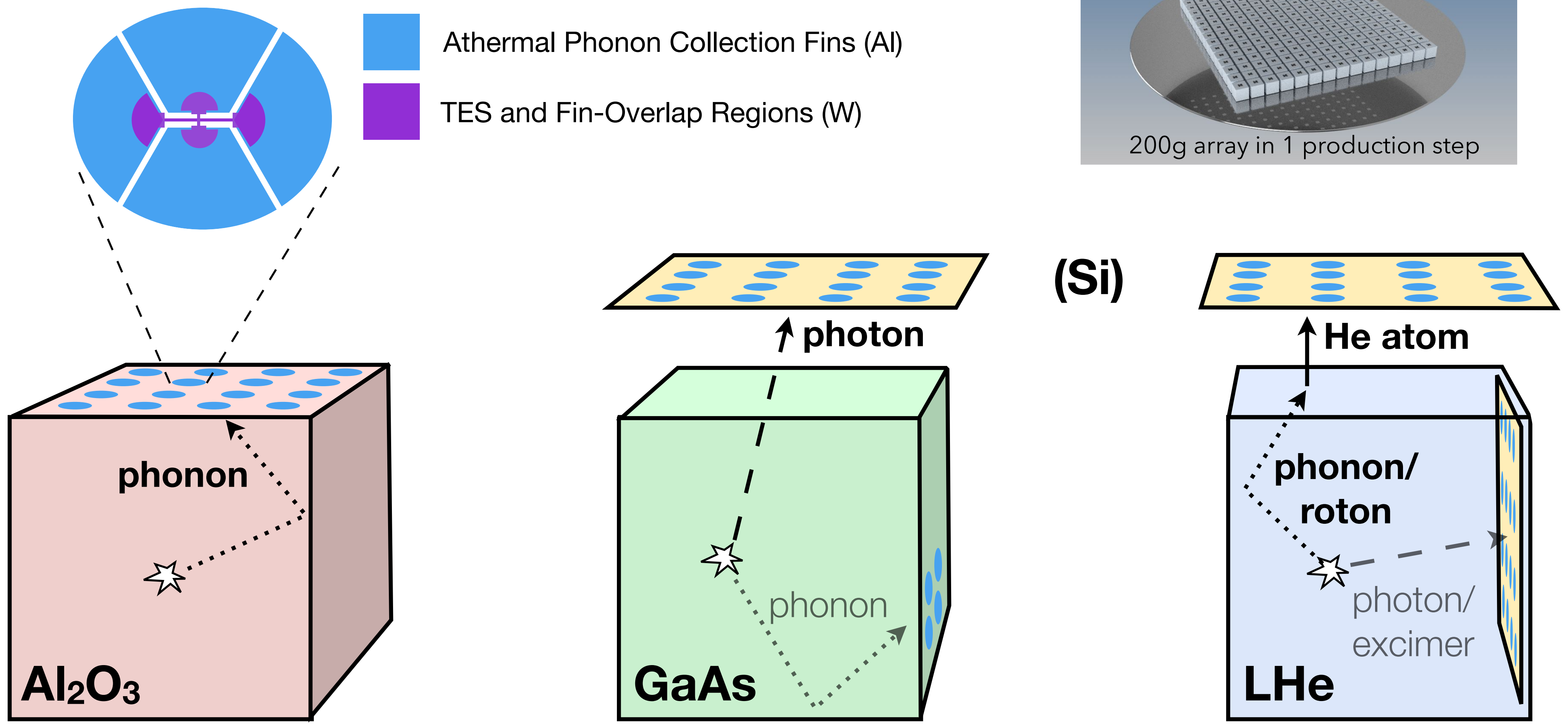
- R&D is needed in the following areas:
  - Lower thresholds
  - Lower noise readout
  - Multiplexing large number of detectors
  - Vibration, EMI, and other environmental noise reduction
  - Radioactive Background Mitigation
  - Other…







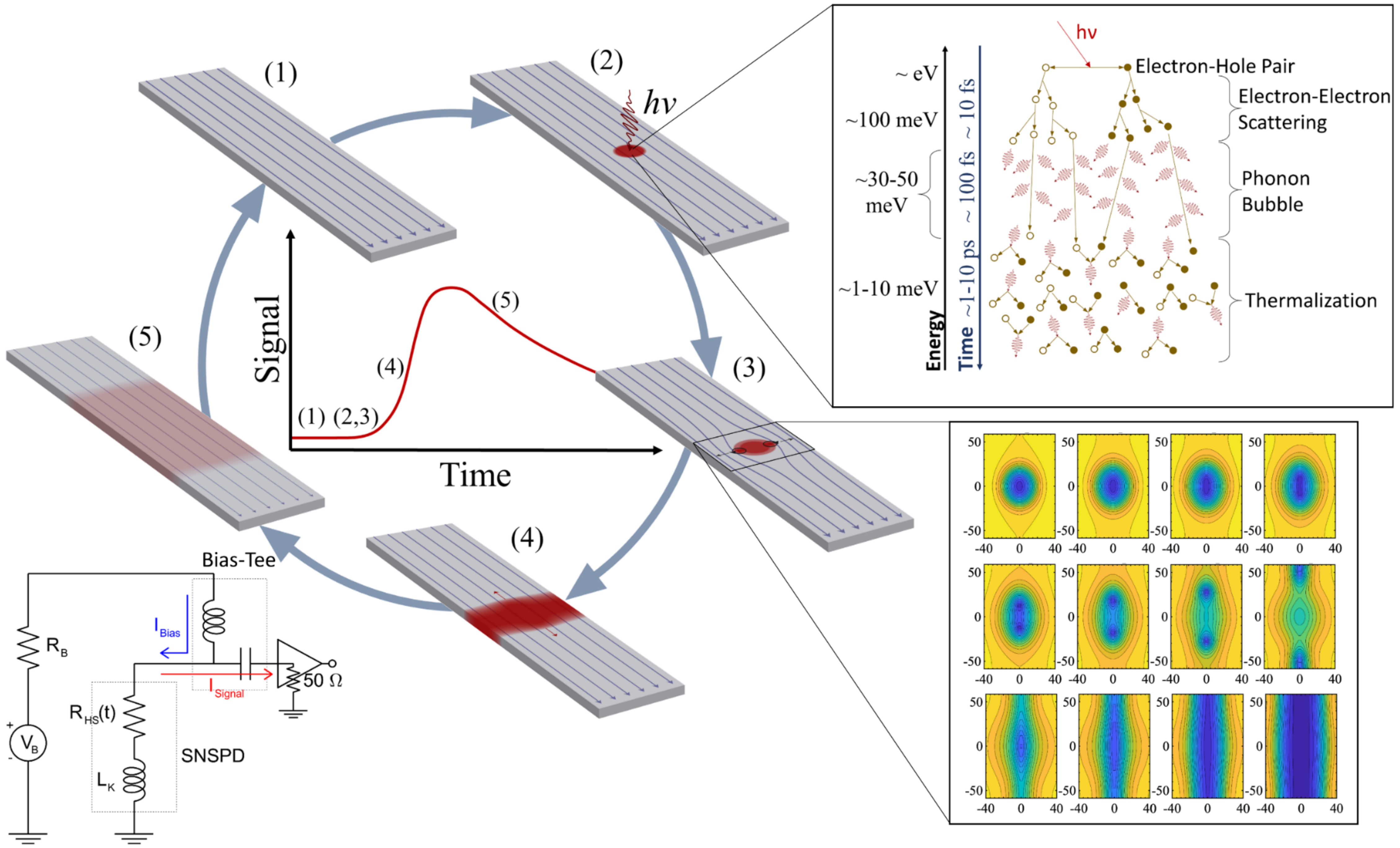




SNSPD

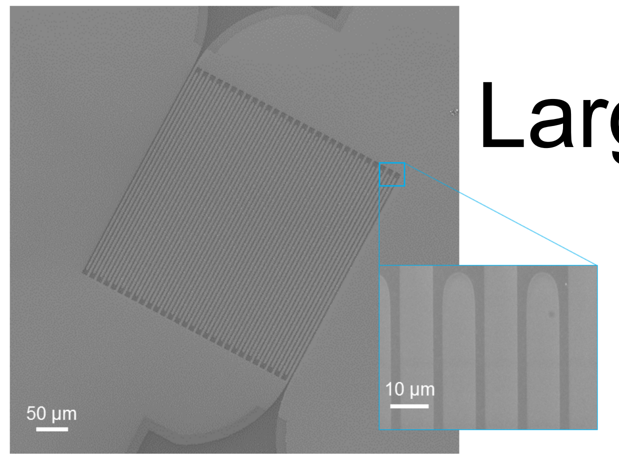
Superconducting Nanowire Single-Photon Detectors (SNSPDs)

Overview: Supercond. Sci. Technol. 25 (2012) 063001



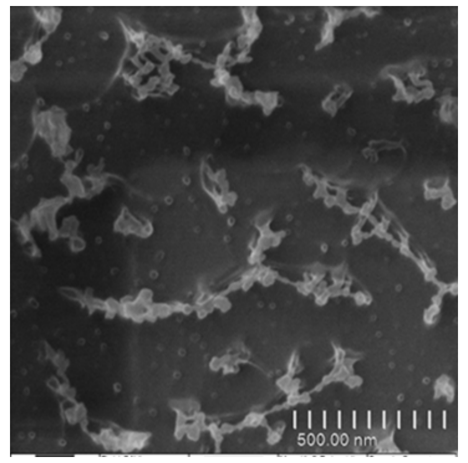
- 98% efficiency demonstrated
- Good efficiency from UV to infrared range
- Count rate > 200 MHZ
- ~ 1 dark count per day
- < 10 ps timing jitter

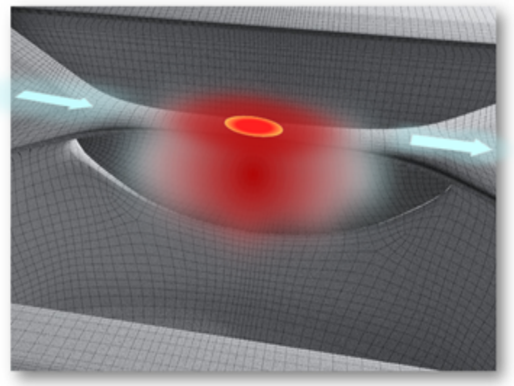
Future prospects



Large-area, cm per side scale detectors

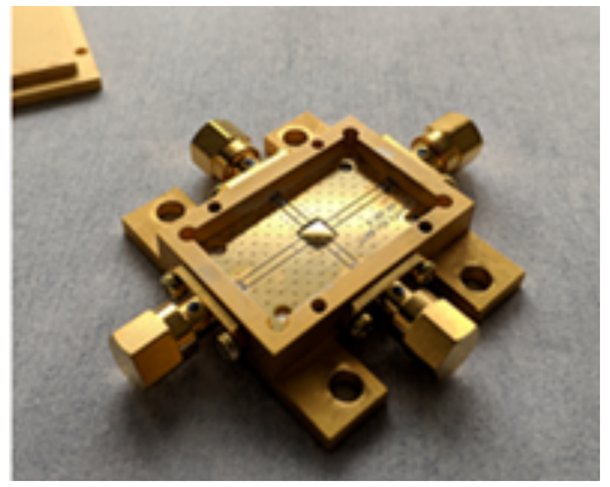
Detection in high-*Tc* nanowires

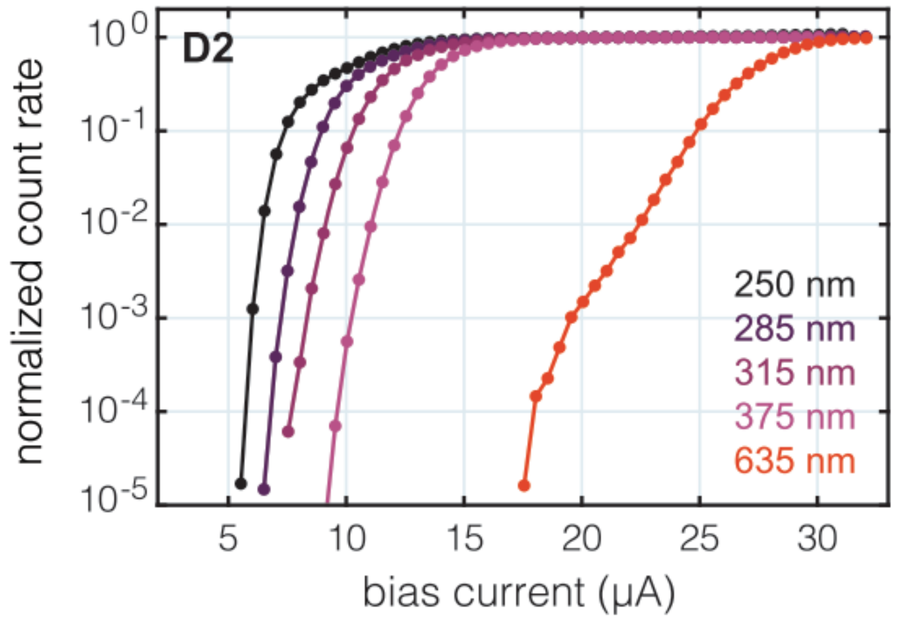




Mid-infrared (20 um and beyond) single-photon detection

Multiplexed readout 100 Megapixel cameras and beyond. Integrated readout to preserve picosecond timing.

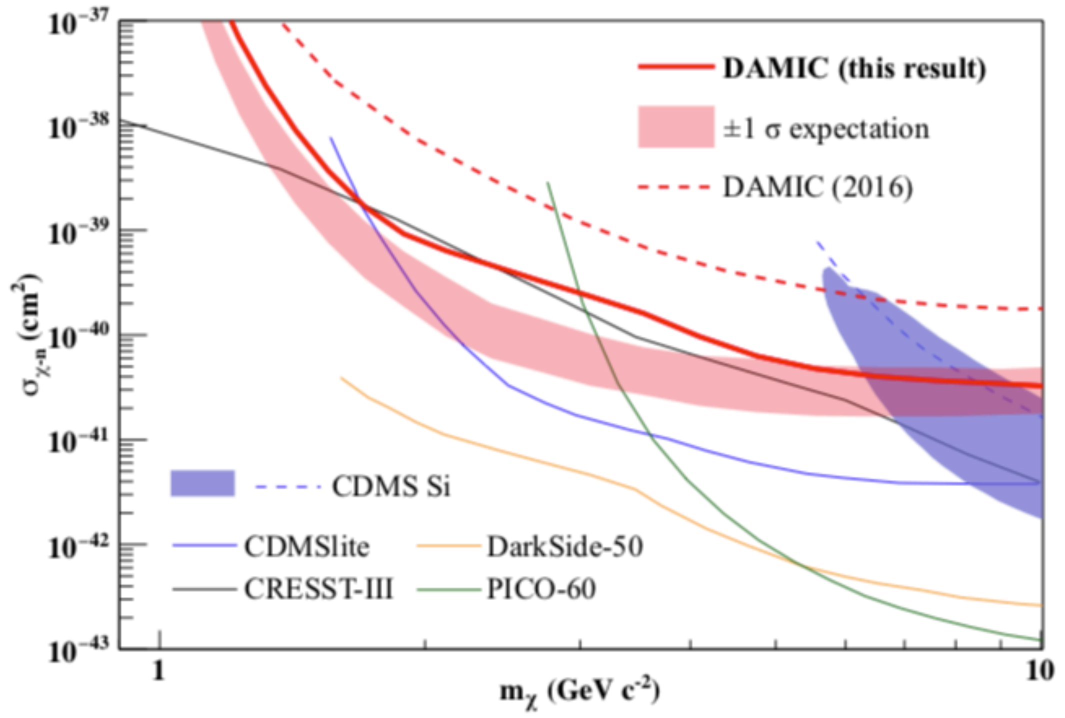


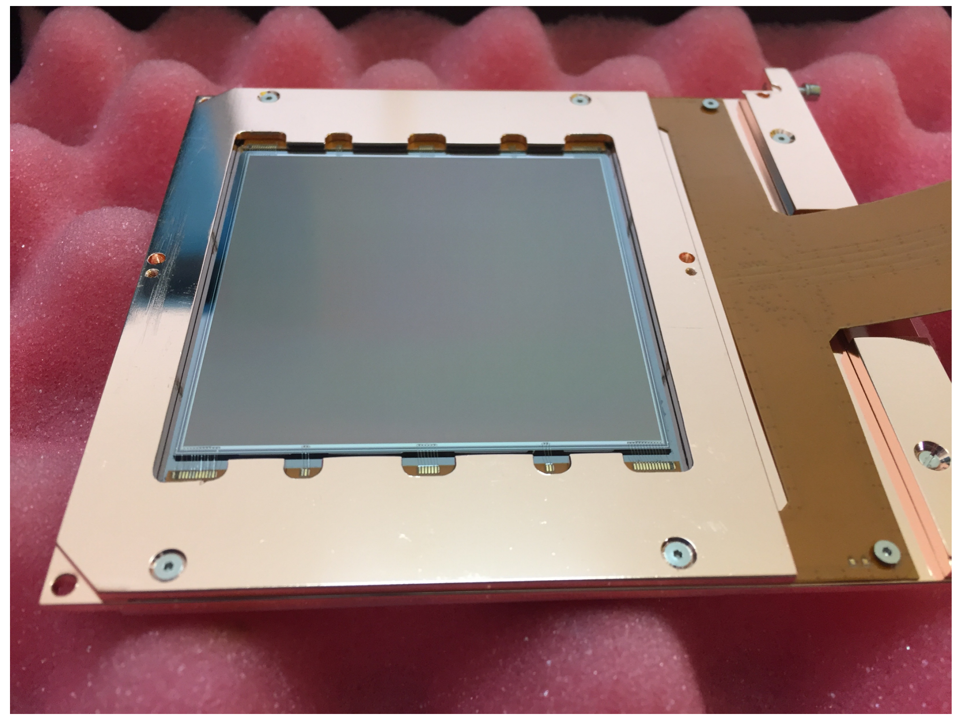


Extend high efficiency operation into Extreme-UV range.

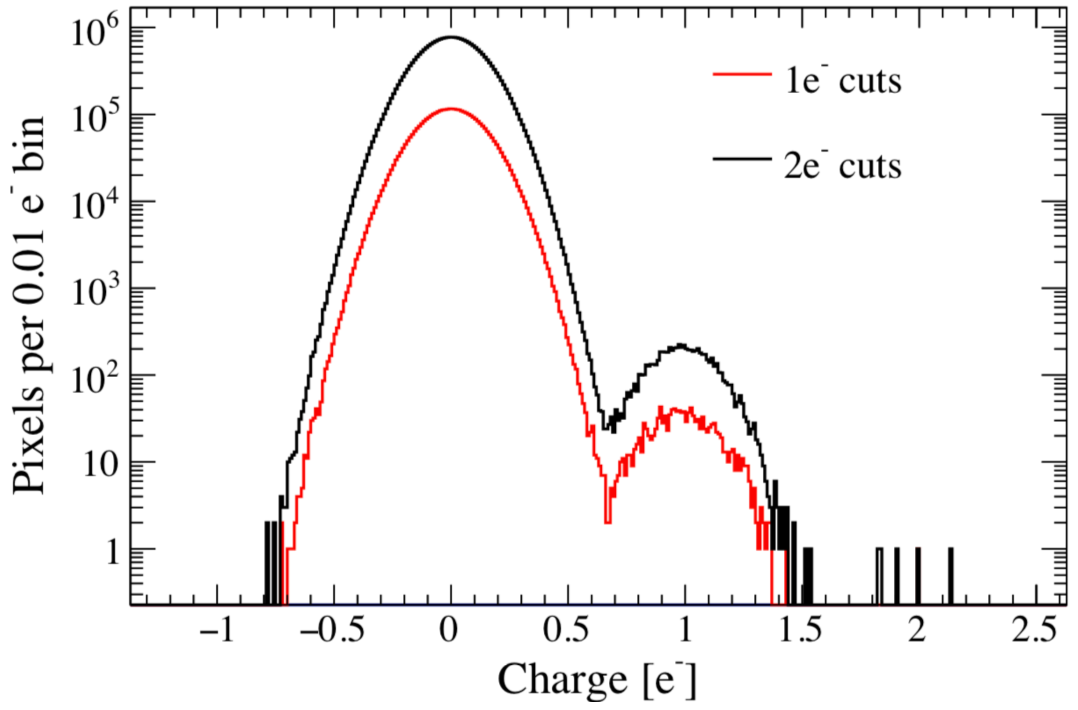
CCDs for DM and Neutrino Physics

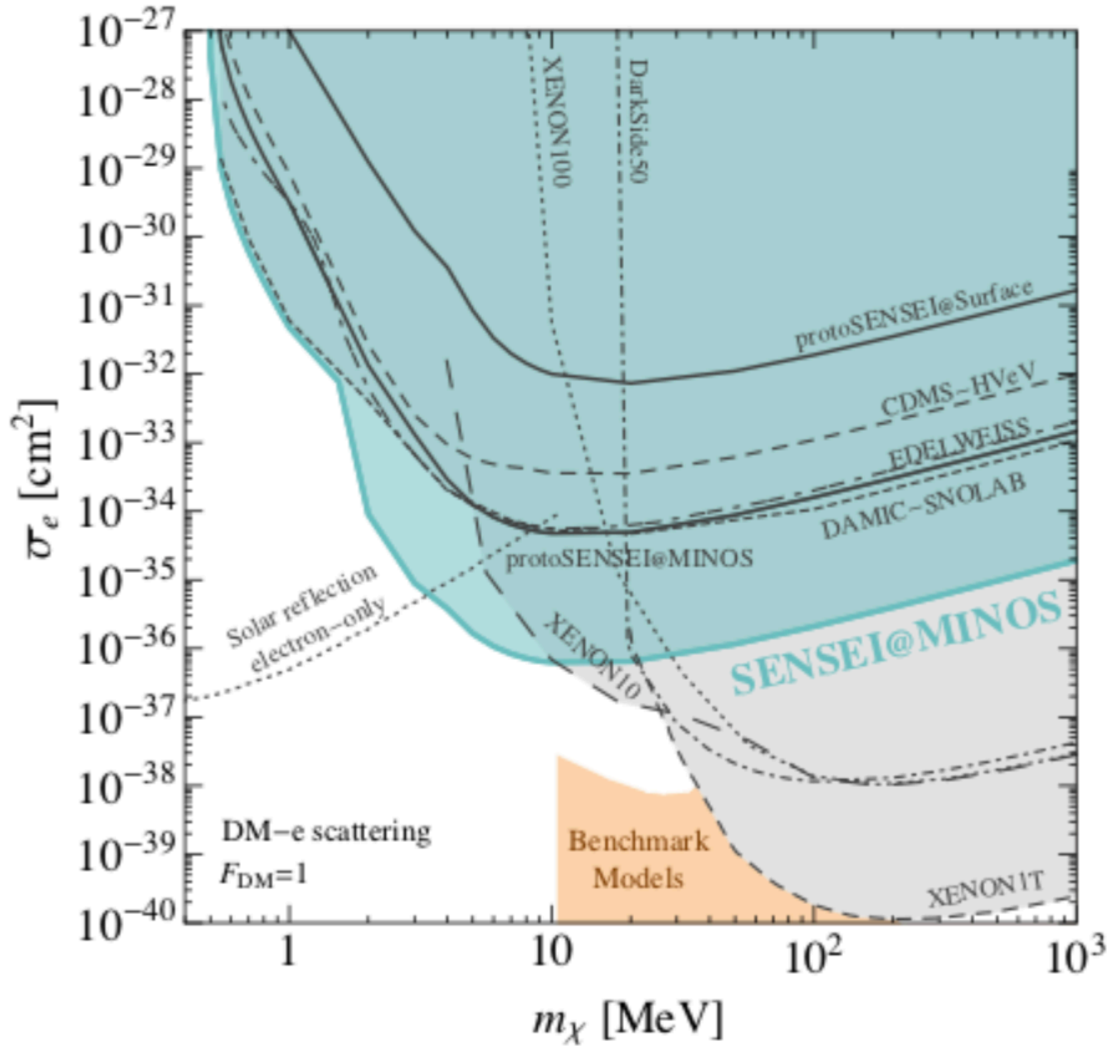
DAMIC: ~50g at SNOLAB completed search for WIMPs with standard CCDs (~70eVee threshold).
arXiv:2007.15622





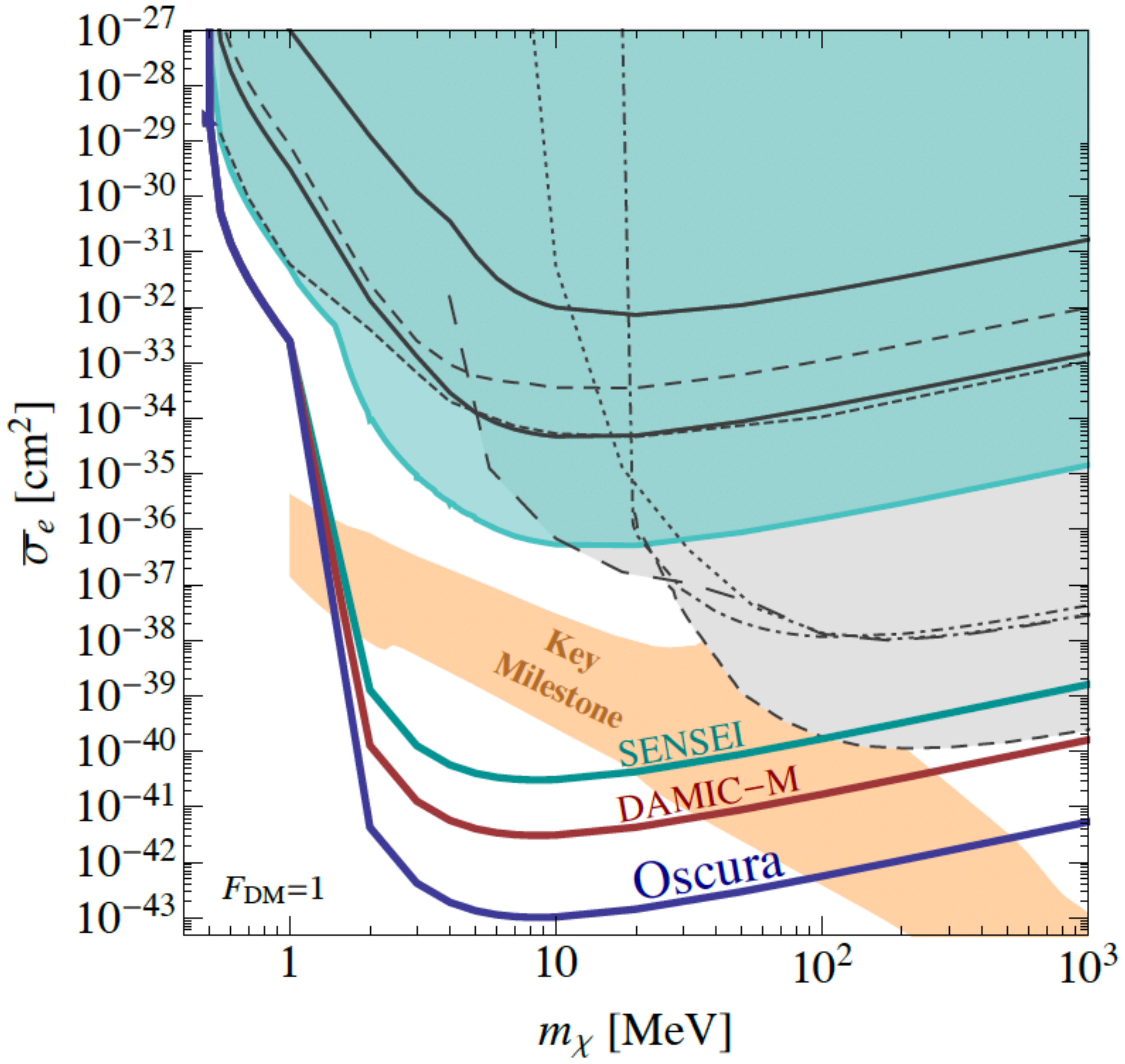
Now: SENSEI ~2 gram detector producing world leading results at shallow underground site (MINOS).
arXiv:2004.11378





Future skipper-CCD projects:
2021(*) : start SENSEI 100g @ SNOLAB
2023(*) : start DAMIC-M 1kg @ Modane
2024(**) : start building Oscura 10kg

(*) fully funded
(**) R&D funded "New Ideas in Dark Matter"

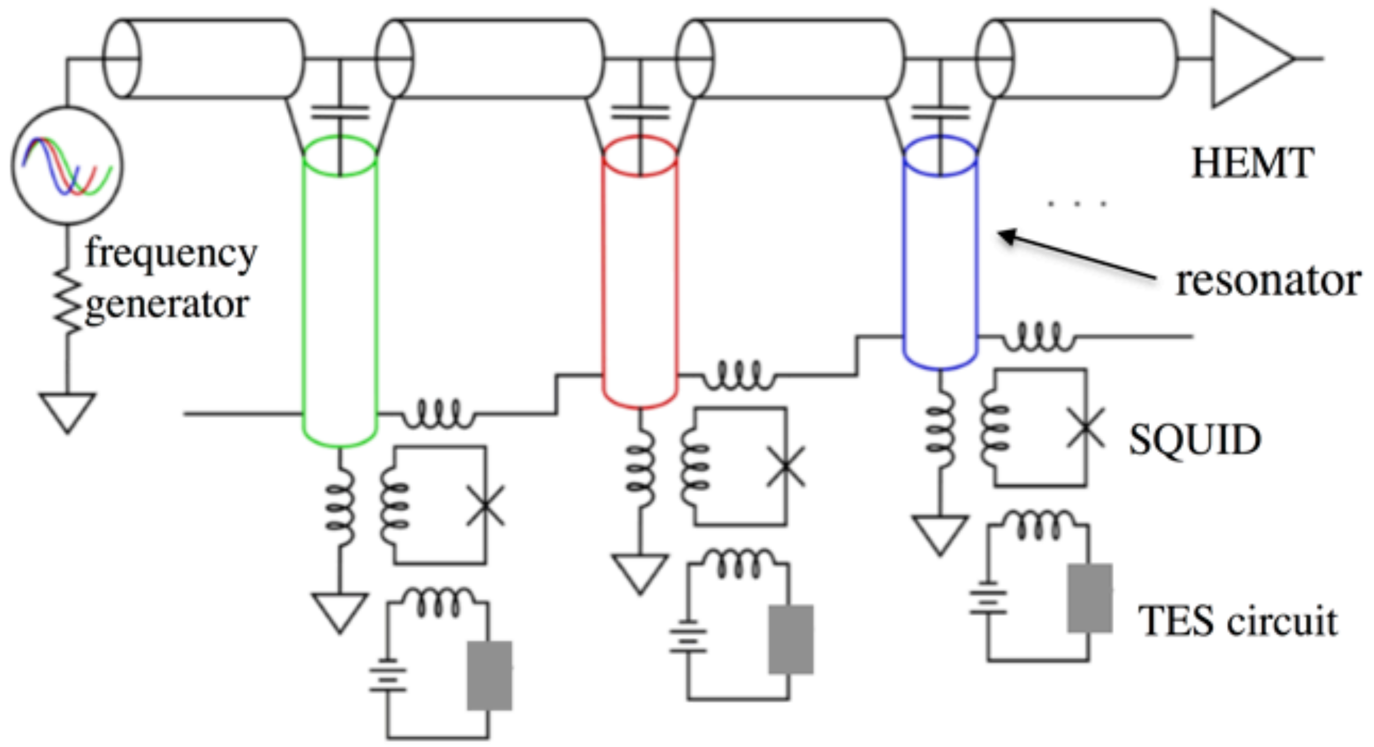


a multi year plan, with a strong community support to take this technology to its full potential.

Readouts

- SQUID MUX: enable thousands of TES/MagCal readout channels in HEP experiments
- MKIDs/uMUX readouts: Lots of overlap between MKIDs and TES microwave MUX readouts in room temp components and DAC. Huge importance for future experiments
- Skipper CCD readout (for example using CMOS) for large mass next-gen experiments.

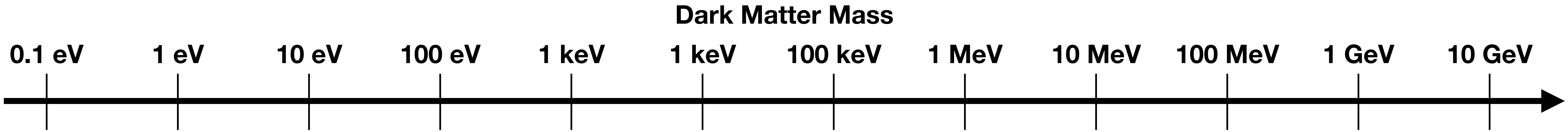
- Multiplexed readout for SNSPDs will allow large area detectors with 100 Megapixels and beyond.



Microwave SQUID multiplexing

Mates et al. , Appl. Phys. Lett. **111**, 062601 (2017)

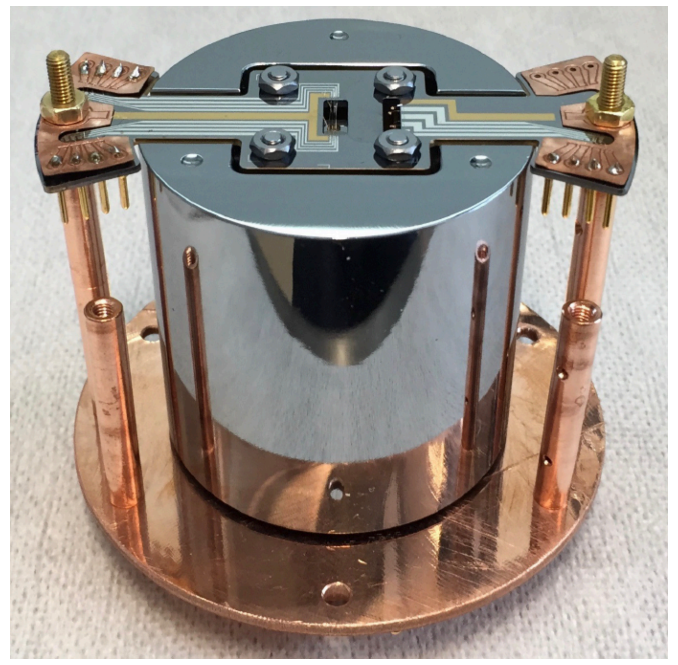
Overlap with Neutrino Physics

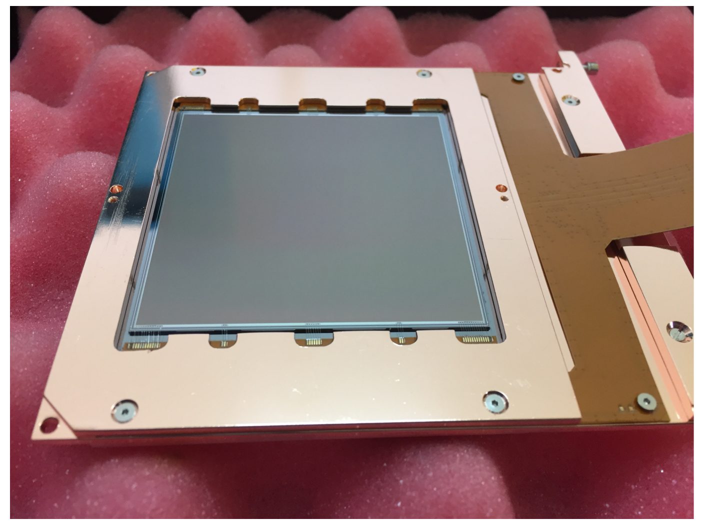


- Low-threshold technologies for light DM searches make excellent CEvNS detectors!
- Low-background large-mass arrays of detectors are needed both for future 0vBB and reaching the DM neutrino floor.
- Low-temperature techniques are shared by many of these experiments.
- Background discrimination and detector calibration are also shared amongst all three physics thrusts.

CEvNS Detectors

0vBB Decay Detectors





Other Ideas

- Theoretical work:
  - Modeling DM/EFT interactions, Quantum Computing algorithms
  - Modeling Quasiparticle transduction and lifetime; non-equilibrium dynamics
- Gravitational Wave detectors and Atomic clocks as DM detectors
- Materials Design for specific sensitivity to correlated quantum phenomena
- Mechanical quantum sensors with levitated mass arrays
- DM search with entangled electron spin qubits in ^{3}He
- Directional detection with solid state using quantum defects in diamond or carbon nanotubes

Conclusions / Questions

- There is a vibrant program of experiments covering the full mass range of particle dark matter.
- Many overlaps with QIS technologies, quantum sensing, axion-like searches.
- Neutrino detectors for both 0vBB and CEvNS have lots of technical overlap with many of these efforts.
- How do we balance technology R&D vs funding specific experiments?
- How can we best package the plethora of ideas into several strongly-motivated recommendations / white papers for our SNOWMASS report?